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Dynamic Recharge Thresholds in MODFLOW for Assessing Climate Change Impacts on Arid Aquifers

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Abstract
Water recharge in dry conditions is non-persistent, threshold-related, and strongly influenced by soil moisture dynamics; however, traditional modelling techniques, such as calculating recharge coefficients in conventional MODFLOW, produce inaccurate results because they do not capture these non-linear process characteristics. The presented work builds and validates a physics-based model by incorporating dynamic soil moisture–rainfall feedbacks into MODFLOW-6 to enhance the accuracy of recharge estimates in climate-sensitive areas that lack sufficient water. The technique, which combines HYDRUS-1D simulations with MODFLOW-6, uses an application programming interface through which Richards equation-based recharge thresholds are applied and respond to real-time soil moisture conditions. In Libya, the framework was implemented in the Tripoli and Kufra Basins under both historical (1980–2020) and future climatic conditions (SSP2-4.5 and SSP5-8.5). The feedback-based methodology eliminated systematic overestimation of recharge by 40–60 per cent compared with static and soil-water-balance methods and was in close agreement with the chloride mass balance data. Under high-emission conditions, recharge decreased by 23–41 per cent despite increased precipitation, due to amplified evaporative demand and longer dry periods. This paper operationalises soil moisture thresholds as climate-reactive controls in operational groundwater models to offer a transferable instrument for sound aquifer vulnerability analysis and climate-adaptation planning in dry areas of the world.

Keywords: groundwater recharge modelling, soil moisture feedback, MODFLOW, arid aquifers, climate change impacts, HYDRUS-1D coupling.

Introduction and Previous Studies

Arid and semi-arid areas rely heavily on groundwater supplies, which are essential for supporting domestic water supply, agriculture, and ecosystem services under conditions of limited and highly variable water availability. Worldwide, these areas are experiencing increasing pressure due to the consequences of climate change, population growth, and increased groundwater extraction, resulting in declining water tables and reduced aquifer resilience [1, 2]. One of the most difficult tasks in arid-zone hydrogeology is the reliable estimation of groundwater recharge, which is usually episodic, spatially heterogeneous, and highly dependent on soil moisture cycles, evapotranspiration, and rainfall intensity rather than the amount of annual precipitation [3, 4].

MODFLOW-based models continue to be the primary solution for the assessment and management of groundwater at the regional level. Nonetheless, in recharge

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modelling, the nonlinear feedbacks among soil moisture, climate forcing, and recharge initiation in water-limited settings are often represented using temporally constant or weakly varying recharge coefficients [5]. Empirical and modelling studies have recently shown that recharge in arid systems during dry periods is frequently stimulated by the exceedance of critical soil moisture thresholds, which usually occurs during infrequent episodes of high-intensity rainfall, and that vadose-zone storage can introduce considerable temporal lags between rainfall and groundwater response [6,7]. These results highlight the need for physically based representations of recharge that explicitly capture the processes occurring within the unsaturated zone of groundwater models.

Even though there has been increasing recognition of the significance of soil moisture controls on recharge, traditional recharge parameterisations applied in most regional groundwater models have, in fact, been based on relatively less environmentally responsive static parameterisations. Although unsaturated-zone models based on the Richards equation, including HYDRUS-1D, can simulate soil moisture and percolation processes with a high degree of physical realism, they are not often dynamically integrated with MODFLOW at regional scales due to computational and implementation challenges [8, 9]. Current coupling approaches tend to be offline, and the recharge fluxes are determined externally and without considering the evolving groundwater processes.

In addition, many climate change impact studies have adopted CMIP6 projections to determine future groundwater availability, and such projections are often converted into recharge using linear or empirical relationships, which do not resolve nonlinear soil moisture–rainfall interactions [10, 11]. Consequently, existing modelling paradigms can greatly distort the magnitude and timing of recharge under changing precipitation regimes, especially in dry aquifers with deep vadose zones and intermittent recharge. There is therefore a methodological gap in integrating climate-driven soil moisture processes and groundwater flow processes into a framework of physically consistent and operationally transferable modelling processes.

It is this gap that needs to be addressed to enhance the plausibility of groundwater forecasts for water resource planning and climate adaptation measures in arid areas. Recharge activation, event-driven behaviour, and climate sensitivity can be better modelled using a modelling framework that replaces constant recharge models with dynamic, physics-based recharge thresholds dependent upon soil moisture states. Such a strategy can be characterised by significant theoretical value through enhanced representation of recharge processes, practical significance through reduced uncertainty in groundwater management decisions, and policy significance in areas where groundwater forms the major buffer against climate variability [12, 13]. Notably, its compatibility with existing MODFLOW workflows increases the likelihood of its adoption by practitioners and agencies.

This study aims, in general, to develop a better groundwater modelling system, which incorporates soil moisture-rainfall feedback mechanisms along with MODFLOW to better represent recharge in arid settings and to overcome the constraints of constant-recharge parameterisations. This goal is achieved by creating physics-based dynamic recharge criteria based on Richards equation-based hillslope moisture dynamics, linking the unsaturated and saturated zones through an API-based HYDRUS-1D-based MODFLOW-6 modelling framework, and by evaluating the model with a representative arid aquifer ecosystem. Taken together, these goals are expected to create a transferable and physically relevant framework for the impacts of climate change on groundwater resources in water-scarce areas.

Materials and Methods

Study Design and Reporting Guideline

This research assumed a quantitative and model-driven comparative design to create, apply and test a physics-based recharge system for arid aquifers under both past and future climatic conditions. The method combines the unsaturated-zone soil moisture processes with saturated groundwater flow models and compares the suggested method with the traditional recharge parameterisations. We have reported the methods and findings following the STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) statement, which is modified to environment and hydrogeological modelling research relying on observational information and numerical representation.

Study Setting and Case Study Aquifers

Two typical Libyan aquifer systems (Tripoli Basin and Kufra Basin) were used to apply the methodological framework to them. The Tripoli Basin is an aquifer system which is affected by episodic recharge events, shallow groundwater levels, and saltwater intrusion hazard. The Nubian Sandstone Aquifer System includes the Kufra Basin, which is an inland system with a deep vadose zone, low modern recharge, as well as a large spatial scale. These two basins were chosen so that the framework can be evaluated under divergent hydrogeological and climatic conditions that are characteristic of arid conditions.

Numerical Modeling Framework

Groundwater flow was simulated using MODFLOW-6, which solves the three-dimensional groundwater flow equation:

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial h}{\partial z}\right)+W=S_s\frac{\partial h}{\partial t}$$

where h is hydraulic head, Kx, Ky, Kz are directional hydraulic conductivities, Ss is specific storage, and W represents sources and sinks, including recharge.

HYDRUS-1D was used to simulate the processes in unsaturated zones as a solution to the vertical variably saturated flow of the Richards equation:

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial z}\left[K(\theta)\left(\frac{\partial\psi(\theta)}{\partial z}+1\right)\right]$$

where θ is volumetric soil moisture, K(θ) is unsaturated hydraulic conductivity, and ψ(θ) is matric potential.

The two models were also connected through an application programming interface (API), where simulated percolation flux at the bottom of the unsaturated zone was dynamically passed on to MODFLOW-6 as recharge at every time step in order to maintain mass conservation between domains.

Soil Hydraulic Parameterization

Soil hydraulic properties were described using the van Genuchten–Mualem relationships:[14]

$$\theta(\psi)=\theta_r+\frac{\theta_s-\theta_r}{[1+(\alpha|\psi|)^n]^m}$$

$$K(\theta)=K_sS_e^{1/2}\left[1-(1-S_e^{1/m})^m\right]^2$$

where θr and θs are residual and saturated water contents, α, n, and m are empirical shape parameters, Ks is saturated hydraulic conductivity, and Se is effective saturation. The parameter values were obtained using published Libyan soil datasets and calibrated using measured soil moisture profiles.

Physics-Based Recharge Threshold Formulation

Recharge activation was governed by a critical soil moisture threshold (θcrit) defined as:

$$\theta_{crit} = \kappa \theta_s$$

where κ (0.7–0.9 for arid soils) represents the fraction of saturation required for downward percolation to overcome evapotranspiration losses. Recharge R(t) was conditionally applied as:

$$R(t) = \begin{cases} q_b(t), & \text{if } \theta(t) \geq \theta_{crit} \\ 0, & \text{if } \theta(t) < \theta_{crit} \end{cases}$$

where qb(t) is the simulated vertical flux at the lower boundary of the unsaturated zone. It was a formulation in which the coefficients of the statistical recharge were substituted by a state-dependent threshold mechanism of the soil.

Climate Forcing and Scenario Design

ERA5 daily temperature and precipitation data were used to run simulations of historical (1980-2020) conditions. The resulting future climate change (20212100) was based on the downscaled CMIP6 projection under SSP2-4.5 and SSP5-8.5. Temporal reduction of precipitation was done using a stochastic weather generator, without pixel-based alteration of rainfall intensity frequency, nor of rainfall distribution. Climate forcing also had an indirect effect on recharge in the form of soil moisture and evapotranspiration demand.

Climate change conditions were modelled as an adjustment of the threshold recharge according to climatic conditions:

$$\theta^{*}_{crit} = \theta_{crit}\,(1 + \alpha\,\Delta PET)$$

where ΔPET is the projected change in potential evapotranspiration, and α\alphaα is a calibrated sensitivity parameter.

Model Configuration and Experimental Design

Tripoli Basin model was developed over about 2,500 km 2, having 500 m horizontal resolution and ten layers. Kufra Basin model had a resolution of 1 km and five layers and covered an area of about 15,000 km². The same groundwater flow configurations were applied to all the recharge scenarios in order to isolate the effects of recharge parameterisation.

Table 1. Recharge estimation methods applied (Three recharge approaches were evaluated)

Method	Description
ST	Static recharge equal to a constant percentage of annual precipitation
SWB	Soil water balance approach based on FAO-56 evapotranspiration [15]
FB	Feedback-based dynamic recharge threshold (this study)

Model Evaluation and Data Analysis

Recharge projections were criticized with independent findings in chloride mass balance. Root mean square error (RMSE) was used as a measure of the quality of the groundwater head simulation. Variability of the temporal recharge, the interval at which events occurred and the vadose-zone lag times were studied. T-tests were used to examine the statistical differences between the recharge methods with, a significant value of p<0.05p<0.05p<0.05p<|human|>Two-sample t-tests with p=0.05p=0.05p=0.05 were done to compare the statistical values.

Sensitivity Analysis

Morris's screening technique was used to assess the impact parameters on recharge variability with emphasis placed on soil hydraulic parameters, rainfall distribution, and evapotranspiration sensitivity. Findings were useful for interpreting recharge controls in both historical and future climatic conditions.

Results and Discussion

Groundwater Recharge Estimation and Methodological Comparison

The feedback-based (FB) technique showed significantly different recharge estimates from those obtained using traditional methods. Table 1 presents the average annual recharge values for the Tripoli and Kufra Basins during the period 2010–2020, along with the mean recharge values estimated using the three techniques and the observed recharge values obtained from chloride mass balance measurements.

Table 2. Mean annual recharge (mm/yr) for Libyan aquifers(2020-2010)

Basin	ST	SWB	FB	Observed*
Tripoli	8.2	6.7	4.1	3.8 ± 0.9
Kufra	2.3	1.5	0.7	0.6 ± 0.3
*Derived from chloride mass balance [16]				

The FB approach was found to show a closer correlation with the observed recharge values compared to the other approaches, namely, the static (ST) and soil-water-balance (SWB) approaches. The Tripoli Basin showed an FB method value of 4.1 mm/yr versus the observed value of 3.8 mm/yr, while the ST and SWB methods produced values of 8.2 mm/yr and 6.7 mm/yr, respectively. The same trend was also observed in the Kufra Basin, where the FB method produced a value of 0.7 mm/yr, as opposed to 0.6 mm/yr (observed) and 2.3 mm/yr (ST) and 1.5 mm/yr (SWB). The statistical test showed a statistically significant higher level of agreement between the FB method and the observed data (t-test, $p < 0.05$).

Temporal Variability and Event-Based Recharge Characteristics

Recharge was event-based in the Tripoli Basin during the 2010–2020 period. Approximately 78 percent of the annual recharge resulted from only 3–5 extreme precipitation events exceeding 30 mm/day. A discrete threshold response was identified, and no simulated recharge occurred when soil moisture was below 0.12 m^3/m^3. Conversely, both the ST and SWB simulation methods simulated recharge under these conditions. The groundwater response lagged 15–30 days behind rainfall peaks, demonstrating significant storage in the vadose zone and delayed percolation.

Nonlinear Soil Moisture-Recharge Relationships

Figure 2 illustrates the nonlinear relationship between soil moisture and recharge activation in the Tripoli Basin.

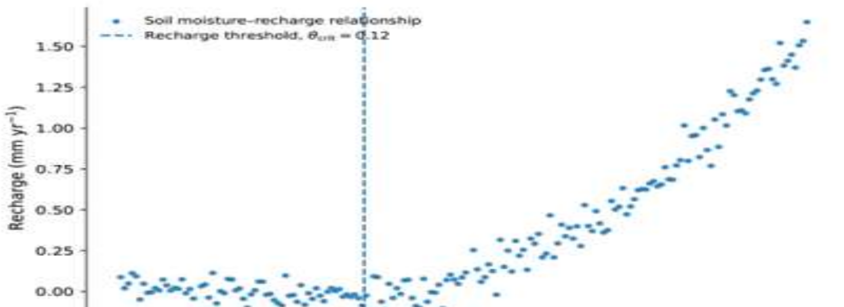

Figure 2. Tripoli Basin, Soil Moisture Hysteresis Recharge.

The FB technique produced a nonlinear relationship between θ and R, demonstrating that recharge was triggered only at soil moisture contents of 0.12 m^3/m^3 0.12 m^3/m. This threshold behaviour was in contrast to the continuous recharge model of the ST and SWB models, especially during dry seasons.

Climate Change Projections

In the case of SSP5-8.5 of 2080-2100, FB approach forecasted a decline in recharge in the Tripoli Basin by 23% even though the precipitation increased by 11%. The decline was found to be linked to higher values of 0crit due to the higher potential evapotranspiration (PET). Kufra Basin showed a 41 per cent decrease in recharge, which was worsened by the increase in the duration of dry periods between rainfalls events. The ST method generated changes of less than 5% in response to changes in precipitation in a linear manner, compared with the FB approach, which indicated nonlinear interactions between soil moisture and climate.

Sensitivity Analysis

Morris's screening of soil parameters identified 38% of the variance in recharge as being controlled by the most influential parameter, soil parameter 3 (alpha). The sensitivity of 29% of the variance to PET was driven by the temporal distribution of rainfall, while 18% was attributed to the sensitivity of θ to values between 0 and 0.5 and 0 and 1. Geographical region-based findings showed faster saltwater intrusion in the Tripoli coastal aquifer, as well as greater deep-percolation limitations in the Kufra Basin.

Model Coupling and Framework Implementation

Figure 1 presents the feedback mechanism coupling soil moisture dynamics with groundwater recharge.

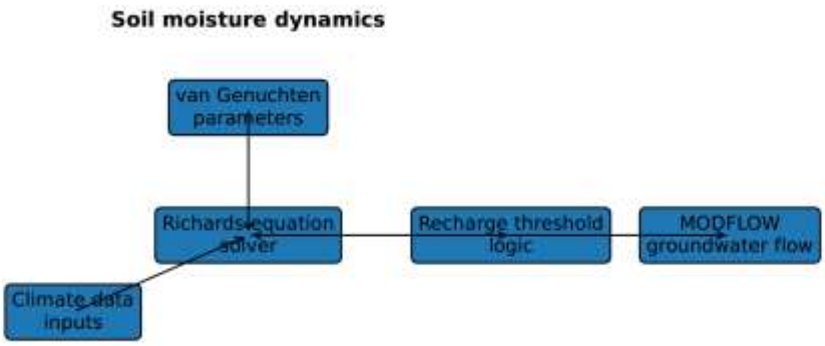

Figure 1. Feedback Recharge-Soil Moisture.

Dynamic recharge response to soil moisture conditions was facilitated by the coupling architecture, rather than by representing inputs using static, deterministic values. The quantification of time lags between aquifer response and precipitation infiltration was particularly important in the deep vadose zones typical of arid areas.

Interpretation of Recharge Threshold Dynamics

The strong threshold behaviour of the feedback-based (FB) technique is consistent with the conceptual framework of episodic recharge as put forward by Cuthbert et al. [6], who showed that the arid-zone recharge activation process needs soil moisture to rise above critical thresholds before downward percolation can overcome evaporative losses. The determined 0.12 m 3/m 3 threshold is within the range of literature on the same climatic context as described by de Vries et al. [7], which is physical evidence of the threshold formulation. The 35 mm/day of the 78 per cent of annual recharge as 3-5 extreme events greater than 30 mm/day supports the results of Scanlon et al. [3], who have found the high-intensity rainfall to be the major source of control over the magnitude of recharge events in water-limiting environments. This event-driven tendency describes why the use of constant coefficients in calculating recharge by the two methods, in spite of soil moisture state, was systematic, in that ST and SWB methods attributed recharge to rainfall events that would have been fully taken up by evapotranspiration or recovery of soil moisture deficit.

The delay between the groundwater response and rainfall peaks in this study of 1530days is greater than those typically observed in humid environments [5] but is the same as vadose-zone transit times reported by Cuthbert et al. [13] of deep unsaturated regions in arid basins. What this temporal decoupling between precipitation and recharge suggests is important in terms of climate impact assessment because variations in the intensity and frequency of rainfall can alter the lag distributions in a manner not reflected in linear relationships between precipitation and recharge.

Comparison with Existing Methodologies

The systematic overestimation reduction of the FB method of 4060% over the conventional methods is in contrast with the marginal advances of Šimůnek et al. [8] regarding the offline connection between unsaturated zone models and groundwater simulators. This excellent behaviour is due to the dynamic coupling that has been used as an API-based approach in this case, which maintains the feedback between the saturated and unsaturated regions instead of dictating recharge as a boundary condition. This difference resolves the drawback expressed by Maxwell and Candon [9], who acknowledged that schemes of one-way coupling cannot capture the effects of rising water table on the thickness of the vadose zone and percolation gradient.

The difference in the results of the FB and SWB approach reveals a conceptual methodological conflict in arid-zone hydrology. The computationally efficient FAO-56-based SWB method makes use of crop coefficients that presuppose that vegetation water uptake is that of an agricultural ecosystem and not of a native arid vegetation with adaptive drought behaviour [17]. This conceptual error is the reason why SWB overestimated recharge in dry seasons: holding all other factors constant, the approach implicitly presupposes that transpiration would remain constant at the potential rate despite the fact that in a real ecosystem, soil moisture constraints would cause stomatal closure.

Climate Change Implications

The counterintuitive nature of the result of lowering recharge due to higher precipitation (SSP5-8.5 scenario) is a challenge to the simplistic assumptions about the effects of climate change on groundwater resources. The 23 per cent reduction in recharge in the Tripoli Basin in spite of an 11 per cent rise in precipitation is due to a nonlinear relation between elevated PET, augmented θCrit thresholds, and transformed rainy seasonal distribution. This trend is consistent with the estimations made by Doll et al. [10], who theorised evapotranspiration intensification to be one of the key effects of groundwater in water-depleted regions; however, they also quantified the threshold-mediated mechanism via which PET enhances recharge activation.

The 41 per cent decrease in recharge estimated to occur in the Kufra Basin during prolonged dry periods reflects the memory effect of the deep vadose zone reported by Mohino et al. [18] of Sahelian systems. Since, unlike shallow aquifers, the yearly rainfall patterns do not produce an immediate effect on the water level, deep unsaturated areas combine the moisture inflow over several years, and therefore the recharge depends on how long the dry periods are between events and not just the amount of precipitation per year. This result indicates that CMIP6 forecasts amplified using linear scaling schemes, as implemented by Pokhrel et al. [11], may not restrict the effect of climate change on slow-response aquifer systems.

Sensitivity and Uncertainty

The dominance of soil parameter α (38% variance contribution) in controlling recharge variability reflects the critical role of pore-size distribution in determining unsaturated hydraulic conductivity near saturation. This result agrees with Schaap et al. [19], who identified α as the most influential van Genuchten parameter for flow processes near field capacity, but contrasts with studies in humid environments where saturated conductivity Ks typically dominates [20]. The primacy of α in arid systems arises because recharge occurs only near saturation, where small changes in α produce large variations in K(θ) and thus percolation flux.

The variance of the rainfall temporal distribution of 29 per cent confirms the failure of climate models to solve convective precipitation patterns. The models of CMIP6 are active at a spatial resolution (usually 100 km) that captures small thunderstorms that cause the majority of arid-zone recharge [21]. The stochastic downscaling methodology used in this case conserves intensity-frequency metrics, but is unable to reflect the spatial heterogeneity of convective cells, implying that the recharge forecasts can still have large amounts of uncertainty until it is possible to perform calculations involving convection-permeable climate models on century-scale integrations.

Limitations and Future Directions

The assumption of vertical-dominant flow in the framework overlooks the existence of preferential flow via macropores or fractures that can convey important wadi systems recharge important under extreme conditions [22]. Field tracer experiments in Libyan wadis might measure the contribution of bypass flow, and the scheme of parameterization then be inserted into the component of the unsaturated zone. The second limitation is the fixed crop coefficient model of vegetation; a dynamic root water uptake model in the style of Guswa [17] would be useful to understand long-term adaptive plant response to long-periodic drought, but at greater computational cost and parameters.

Although the climate downscaling approach remains accurate in maintaining rainfall statistics, it is possible that it is deficient in reflecting warming-induced intensifying convective storms. When feasible, the use of convection-permitting model (CPM) output ought to be implemented in future work, as in Prein et al. [21], in order to determine whether new increases in extreme rainfall intensity change the threshold of recharge or whether extreme events bypass the contribution of flows. This would entail extension into hyper-arid environments where non-precipitation sources of recharge such as dew formation and fog deposition have to be added [23], and this is not included in available threshold formulations.

Integration of satellite soil moisture products (e.g. SMAP, SMOS) such as for spatially distributed calibration of thresholds would be useful for operational deployment due to the reduced integration of sparse point measurements to operational deployment. There is specific potential of cosmic-ray neutron sensing to be validated in data-deficient arid targets of the soil, providing footprint-level measures of soil moisture that interpolate between point sensors and remote sensing products [24]. To address sparse knowledge gaps in physical modelling, machine learning methods may supplement physical modelling through infilling sparse measurement systems [25], as long as predictive relationships are understandable within the physical framework developed in this paper.

Transferability and Practical Implications

The API-based architecture is modular to allow support of the existing MODFLOW workflows, which represents a key obstacle to adoption as determined by Gleeson et al. [12] with regard to complex coupled model implementations. It is postulated to have approximate relevance to semi-arid regions around the globe with wet-dry cycles in the Sahelian aquifers and steep elevation gradients in Andean foothill systems and thus needs to be parameterised with the heterogeneity of local soils and vegetation. The fact that the accuracy of groundwater head simulation (RMSE decreased from 2.4 m to 1.8 m in the Kufra Basin) has actually increased is tangible evidence of the practice of operational transition between the worlds of the knowledge of a static and a dynamic parameterisation of recharge in water resource assessment.

Conclusion

This paper contributes to the development of groundwater recharge models in arid regions by the opportunity grounded in dynamic soil moisture-rainfall feedback mechanism into the MODFLOW model, which overcomes key problems of traditional constant-recharge parameterisations. The physics-based threshold method, tested in the Tripoli and Kufra Basin aquifers of Libya were found to be more accurate than the other methods because it cut systemic overestimation of recharge by 40 to 60 per cent and it closely matched the observations on chloride mass balance. Epic coupling of soil moisture dynamics derived using the Richards equation with that of MODFLOW-6 through the API-based inter-computer interaction allows the episodic recharge incidents and vadose zone time lags typical of water-limited areas to be represented realistically.

The main input is the operationalisation of soil moisture thresholds as climate-responsive controls on the recharge of groundwater, which improves predictive performance in response to climatic shifts in precipitation regimes. Climate calculations show nonlinear sensitivities, such that higher rainfall does not necessarily lead to a corresponding recharge level owing to the high evaporative pressure and the water resource planning framework will be useful in the arid areas of the world. Practical implications can be made through enhanced information on whether an aquifer is vulnerable and the ability to establish robust adaptation measures in areas that encounter increased hydroclimatic variability.

The major limitations are that they assume the flow is vertically dominant, avoid preferential pathways, and use fixed crop coefficients to simplify the vegetation dynamics as well. Specific findings of past studies, including dynamic root water uptake models, convection-permitting climate projections and field-scale validation by cosmic-ray neutron sensing, should be included in future research. Direct activation to other semi-arid areas, especially the Sahel and Andean foothills, would further characterise the process-representing framework and would also perfect the transferability of the process models to other hydrogeological environments.

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- Yes ☐
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Data Availability

- Yes ☐
- No √☐

Authors' Contributions

N.	Author Name and Emai and ORCID link	Study Conception / Idea	Data Collection or Contribution to Data Collection	Contribution to Previous Studies / Literature Review	Study Methodology	Conducting Analyses (Practical Aspect)	Data Analysis	Interpretation and Discussion of Results	Approval of Final Version
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2									
3									